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Development of design optimized simulation tool for water desalination system

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HIGHLIGHTS

- Simulation of an HDH system driven by a compound concentrator is conducted.
- A comparison between experimental data and simulation results shows a good agreement.
- Fresh water production rate lies between 1 and 3.5 kg/h based on the season.
- Optimized performance factor reaches a maximum of 0.85 in summer season.
- A robust design tool for HDH desalination was developed with maximum error of 5.8%.

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ABSTRACT

Up to half of the world's population faced growing water crisis at an alarming rate especially in developing countries such as African countries. Thus, with abundant salty water and solar intensity in those regions, solar powered desalination system presents an attractive solution towards availability of clean water. Humidification/dehumidification desalination system is considered as a competitive solution between many desalination systems. Its performance depends on the matching between site weather conditions and different design parameters. This fact proves the urgent needs for a robust design tool that is capable of predicting the desalination system performance at a certain location before implementation decision. The present work developed a simulation design tool based on TRNSYS and EES programs that could predict the system performance. Previously published experimental data were utilized for the validation process where a maximum error of about 5.8% achieved. The developed tool was applied on EL-ARISH region, as an example of remote areas. Results showed that an output of 1 kg/h fresh water rate requires about 15 m^2 of the compound parabolic trough collector operating at average solar intensity of 1000 W/m^2. An optimization technique was integrated to the developed model to improve the matching between the system operating parameters and site weather conditions.

1. Introduction

The vast majority of Egyptian populations are mainly concentrated in the Nile Valley and the Delta as well as in the coastal zone along the Mediterranean Sea. Consequently, the Egyptian government has developed a strategy for future urban development and population redistribution [1]. Due to the continuous increase in population and the augmented use of water for agriculture [2–4] and industry [5] as well as the urbanization of many areas, the demand for both energy and water will continue to rise, i.e. energy and water will be the essential challenges for future urban development plan. Seawater desalination is a promising technology to reduce water problem while renewable energy can be used to save energy [6]. Seawater desalination is a process of reducing dissolved minerals in seawater to become fresh water that should contain as a maximum concentration of 500 ppm according to World Health Organization (WHO). Desalination can be achieved by using either thermal techniques or membrane-based techniques.

Among thermal techniques, humidification/dehumidification (HDH) desalination process is regarded as a favorable technique for small and medium capacity production plants. This is due to its attractive benefits such as simplicity, cost effective, low pay back, etc. [7]. Moumouh, et al. [8] carried out a technical review of solar thermal energy combined with humidification-dehumidification process for desalination brackish water. They confirmed that the HDH desalination system using solar energy is a simple technology particularly suited for regions in developing countries where there are very low infrastructure and unskilled labor.

A number of studies were conducted to analyze the performance of seawater desalination system using solar non-concentrating and concentrating collectors. A parametric study of a HDH desalination system

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Nomenclature

Symbol

ω	Humidity ratio [kgwv/kgda]
$\dot{M}$	Mass flow rate [kg/h]
$\dot{Q}$	Rate of energy change [kW]
$\dot{P}$	Power
Cp	Specific heat [J/kg.K]
h	Specific enthalpy [kJ/kg]
hl	latent heat of condensation [kJ/kg]
PF	performance factor [-]
$\dot{Q}_{in}$	Rate of energy input to the system [kW]
$\dot{Q}_{out}$	Rate of energy given up in order to obtain fresh water [kW]
RH	Relative humidity
Ta	Ambient (air) temperature [°C]

Subscript

a	Air
aux	Auxiliary
b	Blower
cond	Condensation
fw	Fresh water
humid	Humidification
i	Point i
in	Inlet condition
op	Oil pump
out	Outlet condition
sol	Solar
swp	Seawater pump
w	water

Abbreviations

CPC	Compound Parabolic Concentrator
HDH	Humidification Dehumidification
LST	Locar Solar Time
PTSC	Parabolic Trough Solar Collector
WHO	World Health Organization

Greek Symbols

θa	Half acceptance angle

carried out by Yildirum and Solmus [9], Sharqawy, et al. [10] and Farsad et al., [7] using solar air and water heaters. Chang et al., [11] determined the experimental performance characteristics of multi-effect HDH system with the use of packed porous plastic balls and finned heat exchangers under different heating temperatures, the seawater flow rates and the air flow rates. They noted that the system performance could be improved through optimization of the system design and operating conditions. Hamed et al., [12] theoretically and experimentally investigated the performance of a solar HDH desalination system to predict the effect of different operating parameters on the system thermal performance. Their results showed that the system productivity is about 22 l/day and the best operating time for HDH system during the day ranges from 13 to 17 pm. Kang et al., [13] developed a mathematical model of a triple-stage regenerative humidification-dehumidification desalination system based on mass and energy balances in its components. Their results revealed that this system could be used to produce the good quality of distilled water for drinking and irrigation. Elminshawy, et al., [14] conducted an experimental and analytical investigation on a novel solar HDH system to enhance the fresh water productivity. Nada, et al., [15] theoretically investigated the performance of hybrid air-conditioning (A/C) and HDH desalination systems to save energy consumption of the air conditioning system and to produce fresh water. The effect of fresh air ratio, space supply air temperature, outside air wet bulb temperature on the fresh water productivity, refrigeration capacity, compressor power and percentage of power saving are presented.

Concentrating solar collectors coupled with desalination systems have more potential compared to non-concentrating solar collectors [16]. Thermodynamic analysis of a HDH system driven by a parabolic trough solar collector (PTSC) was conducted by Al-Sulaiman et al., [7]. Their results revealed that PTSCs are well suited for air heated HDH systems for high radiation location, such as Dhahran, Saudi Arabia. Compound parabolic trough collector represents one of the most matured technologies [17]. It has been successfully used in many large-scale high-temperature solar plants [18,19]. The most important feature of concentrator is that the single curved focusing surface in the concentrator is replaced with a multiple curved focusing surface. This enables the high temperature solar receiver to be synchronously heated by the upper and lower surfaces of the concentrator, hence, the receiver efficiency increased. Because the focus line of the concentrator is positioned at the bottom of the unit, both diffuse and direct beam solar radiation could be captured by the absorber. This improves the heat preservation of the receiver [16]. Additionally, no needs of sun tracking due to small concentration ratio [20].

From the literature survey, it is found that HDH desalination system driven by a compound parabolic concentrator (CPC) is not reported. Hence, the present work deals with HDH desalination system driven by a CPC under climatic conditions of El-Arish city, Sinai-Egypt, as an area that suffered from water scarcity. The main objective of the present work is to analyze and optimize a solar compound parabolic collector assisted HDH desalination system under climatic condition of EL-ARISH city, which is included in the Egyptian development plan. In order to achieve the research objective, simulation and optimization studies are carried out on the proposed system, which consists of solar energy field subsystem and desalination subsystem. Simulation design tools based on TRNSYS 16 [21] and EES [22] are used to develop simulation programs for each component of the proposed system to predict the effect of operating parameters on the system thermal performance. Then, optimization techniques of GenOpt program are applied to improve the matching between the system operating parameters and site weather conditions.

2. System description

Fig. 1 shows a schematic diagram of a solar desalination system under investigation. It includes a solar closed loop, a seawater path and an air path. The solar closed loop comprises a compound parabolic concentrator (CPC), a hot water tank and an oil pump. The CPC consists of a concentrating reflectors and an absorber as shown in Fig. 2. The focus of each parabola coincides with the intersection of the absorber and the opposite wall. The CPC collects both direct beam radiation and diffuse radiation, which approach the aperture within a critical angle (θ_a) called the half-acceptance angle. The seawater path contains a dehumidifier, a heat exchanger, and a hot water tank, a humidifier and two seawater pumps. The air path includes a blower, a humidifier and a dehumidifier. Hot seawater is then sprayed to humidify the incoming air in the humidification chamber. The humidified air then enters the dehumidification chamber to be cooled down by the new incoming seawater. In the meantime, the cool seawater is pre-heated to recover heat within the condensation process. The moisture is condensed out and the pure water is accumulated at the base of the chamber, and the dehumidified air is discharged to atmosphere.

2.1. System simulation

For the energy balance and governing equations of the system components the following assumptions are considered;

- The temperature distributions of the water along the absorber tube of the solar collector are dependent on the distance from the inlet axis and the time.